

How to simulate a universal quantum computer using negative probabilities

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Abstract. The concept of negative probabilities can be used to decompose the interaction of two qubits mediated by a quantum controlled-NOT into three operations that require only classical interactions (that is, local operations and classical communication) between the qubits. For a single gate, the probabilities of the three operations are 1, 1, and -1 . This decomposition can be applied in a probabilistic simulation of quantum computation by randomly choosing one of the three operations for each gate and assigning a negative statistical weight to the outcomes of sequences with an odd number of negative probability operations. The maximal exponential speed-up of a quantum computer can then be evaluated in terms of the increase in the number of sequences needed to simulate a single operation of the quantum circuit.

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1. Introduction

The observation that quantum systems can under some circumstances outperform comparable classical systems is a central motivation of quantum information research. In one of the earliest proposals of quantum computation, Richard Feynman pointed out that the difficulty of simulating quantum systems on a classical computer was evidence of the superior efficiency of a quantum computer [1]. In the same presentation, he also describes an attempt to simulate quantum statistics by decomposing the density matrix into probabilities. Since this decomposition results in negative probabilities, the conclusion is that a classical simulation of quantum probabilities is not possible. Nevertheless, negative probabilities can be a useful tool in the “resolution” of quantum paradoxes such as the violation of Bell’s inequalities [2, 3, 4] and the observation of measurement results outside the normal range in weak measurements [5, 6, 7, 8]. Since such paradoxes appear to be closely related to the efficiency of quantum computation, it may be worthwhile to update Feynman’s negative probability approach to quantum computation by describing the operation of a universal quantum computer in terms of negative probabilities.

Specifically, negative probabilities can be used to decompose the entangling multi-qubit gates of a universal quantum computer into statistical mixtures of non-entangling local operations. These non-entangling local operations can be simulated efficiently by a classical probabilistic computation that only needs to keep track of the local qubit states, e.g. by representing them as classical spins, as suggested in the context of NMR quantum computation [9]. It is thus possible to represent the quantum statistics of the computation entirely in terms of the classical statistics of an analogous spin system, simply by including a single additional marker bit that distinguishes negative from positive probability contributions. By choosing a minimally negative decomposition of the entangling gate operation, it is possible to design a classical probabilistic simulation of the quantum computation that not only produces the correct output statistics, but also allows a step-by-step analysis of the computation. The effects of the non-local quantum coherence expressed by entangled states can thus be represented in terms of negative probabilities of entirely local states. Since negative probabilities add up just like positive ones, the correct output probabilities of the quantum formalism can be obtained from the output frequencies of the classical simulation by simply assigning a negative statistical weight to sequences with an odd number of negative probability operations, providing a recipe for stochastic simulations that emphasizes the similarity of the quantum formalism with classical statistics.

In the following, it is shown that a quantum controlled-NOT gate can be expressed as a statistical mixture of three local operations with probabilities of 1, 1, and -1 , which is the minimal negativity for this entangling gate. The gate operation can then be simulated classically by attributing a negative statistical weight to those outcomes that were obtained from operations with negative probability. Since the quantum controlled-NOT gate is universal in the sense that any quantum computation can be constructed

using only quantum controlled-NOT gates and local operations [10], this negative probability decomposition can be applied to obtain a classical probabilistic simulation of any multi-qubit quantum operation. In this simulation, each circuit with N two qubit gate operations is described by a set of 3^N sequences of local operations with positive and negative probabilities. As a result, the statistical relevance of each individual outcome is reduced by a factor of $1/3^N$, and the number of classical runs needed to simulate a single run of the quantum circuit increases exponentially with the number of two qubit gates. The direct comparison of the universal quantum computer using quantum controlled-NOT gates and its corresponding classical probabilistic simulation therefore indicates that in principle, an exponential speed-up of up to 3^N may be achieved by the use of entangling gate operations.

2. Local decomposition of a single entangling gate

The starting point for any negative probability decomposition of quantum operations is the process matrix representation, which corresponds to the density matrix representation for quantum states. The elements χ_{ij} of the process matrix of a quantum operation on a d -dimensional Hilbert space are defined using a basis set of d^2 orthonormal operators \hat{A}_i . The effect of the operation E on an arbitrary input density operator $\hat{\rho}$ is then given by

$$E(\hat{\rho}) = \sum_{i,j=1}^d \chi_{ij} \hat{A}_i \hat{\rho} \hat{A}_j^\dagger. \quad (1)$$

In the case of separate systems, the operators \hat{A}_i are usually defined by products of local basis operators. In such a local operator basis, a completely diagonal process matrix represents a mixture of correlated local operations with no entanglement capability. However, entangling operations have coherences between their local components that cannot be represented by positive mixtures of local products. Any decomposition into a weighted sum of local operations will therefore include some negative weights.

In the case of two qubit operations, a convenient set of basis operators is given by the two qubit products of the Pauli operators X , Y , Z , and the identity I [11]. By themselves, these operators describe π -rotations around the corresponding axes of the Bloch vectors representing the qubits. All other operations are described by coherent superpositions of these operators. In particular, the quantum controlled-NOT operation is given by the coherent superposition

$$\hat{U}_{\text{CNOT}} = \frac{1}{2} (I \otimes I + Z \otimes I + I \otimes X - Z \otimes X). \quad (2)$$

The process matrix of the quantum controlled-NOT therefore includes maximal coherences between all four basis operations. Taken separately, these coherences can also be obtained from local operations on the two qubits, but the combination of all of the coherences results in a gate with maximal entanglement capability.

As shown previously elsewhere [12], the process matrix of the quantum controlled-NOT gate can be decomposed into a sum of three local operations reproducing the

coherences and a negative dephasing term that effectively restores the full coherence of the original quantum gate. It is then possible to identify specific sets of coherences with directly observable local operation, providing an experimental criterion for quantum parallelism [13]. In the present context however, the goal is to minimize the negativity of the decomposition. This can be achieved by combining the negative dephasing operation with one of the positive operations. The process matrix is then decomposed into only three local components: two positive ones with the same coherence as the quantum controlled-NOT, and one negative one with the opposite coherence,

$$E_{\text{CNOT}}(\hat{\rho}) = L_1(\hat{\rho}) + L_2(\hat{\rho}) - \bar{L}_3(\hat{\rho}). \quad (3)$$

For reasons of symmetry, it is convenient to choose the coherences $\chi_{II,ZI}$ ($\chi_{II,IX}$) and $\chi_{IX,ZX}$ ($\chi_{ZI,ZX}$) to define the positive operation L_1 (L_2), and the coherences $\chi_{II,ZX}$ and $\chi_{IX,ZI}$ to define the negative operation \bar{L}_3 . The first set of coherences is described by the local operation

$$\begin{aligned} L_1(\hat{\rho}) &= \hat{M}_{Z0} \hat{\rho} \hat{M}_{Z0} + \hat{M}_{Z1} \hat{\rho} \hat{M}_{Z1} \\ \hat{M}_{Z0} &= \frac{1}{2}(I + Z) \otimes I; \quad \hat{M}_{Z1} = \frac{1}{2}(I - Z) \otimes X. \end{aligned} \quad (4)$$

This operation describes a local measurement of Z on qubit 1, followed by a conditional rotation X on qubit 2 if the result was -1 , which corresponds to a logical 1 of the control qubit. It is thus a local implementation of the controlled-NOT operation in the computational basis. Similarly, the second set of coherences is described by the local operation

$$\begin{aligned} L_2(\hat{\rho}) &= \hat{M}_{X0} \hat{\rho} \hat{M}_{X0} + \hat{M}_{X1} \hat{\rho} \hat{M}_{X1} \\ \hat{M}_{X0} &= \frac{1}{2}I \otimes (I + X); \quad \hat{M}_{X1} = \frac{1}{2}Z \otimes (I - X). \end{aligned} \quad (5)$$

This operation describes a local measurement of X on qubit 2, followed by a conditional rotation Z on qubit 1 if the result was -1 . It is a local implementation of the reverse controlled-NOT operation observed in the X basis, which is complementary to the operation in the computational basis [14, 15]. Finally, the third set of coherences is described by the negative operation

$$\begin{aligned} \bar{L}_3(\hat{\rho}) &= \frac{1}{2}\hat{U}_a \hat{\rho} \hat{U}_a^\dagger + \frac{1}{2}\hat{U}_b \hat{\rho} \hat{U}_b^\dagger \\ \hat{U}_a &= \frac{1}{2}(I + iZ) \otimes (I - iX); \quad \hat{U}_b = \hat{U}_a^{-1}. \end{aligned} \quad (6)$$

This operation describes a correlated pair of $\pi/2$ rotations around the Z and X axes of qubit 1 and 2, respectively. Since this is the operation with negative probability, the correlation between the rotations is opposite to the one that can be observed in the actual operation of a quantum controlled-NOT [13].

For the following analysis, it is essential that the decomposition given above has the lowest possible negativity possible for an input state independent decomposition of the quantum controlled-NOT gate. Specifically, it needs to be shown that the remaining negative probability of -1 is the minimal negativity necessary to explain the entanglement capability of the gate. Since the quantum controlled-NOT can generate a maximally entangled state from local inputs, this problem is equivalent to showing that

the minimal negativity of a local decomposition for a maximally entangled two qubit state is -1 . Since it is well known that the maximal overlap between a local state and a maximally entangled state of two qubits is $F = 1/2$, the overlap of the maximally entangled state with a normalized mixture of local states with positive probabilities of $1 + n$ and negative probabilities of $-n$ is limited to $F \leq (1 + n)/2$. Hence, a negative probability of at least -1 is necessary for a local decomposition of the maximally entangled state, and likewise for the quantum controlled-NOT or any other maximally entangling two qubit gate.

The discussion above proves that the negative probability in eq.(3) is the minimal negativity necessary for a representation of the entanglement capability of the gate. The negativity of the decomposition is therefore a direct measure of the non-local content of the gate operation [16, 17]. Further reductions of negativity are only possible if some assumptions are made about the possible input states. That is, the decomposition should be optimal for any quantum circuit designed to efficiently process completely arbitrary input states. In conventional quantum circuits, more efficient simulations are possible because the input states are either well defined, or limited to eigenstates of the computational basis. Thus, conventional quantum circuits are usually designed to process only classical information, restricting their operation to a tiny segment of the available Hilbert space. The simulation proposed here has the advantage that it can be applied without further analysis of these restrictions imposed on a specific circuit. It thus applies even to a universal quantum computer able to process quantum information directly, without state preparation and measurement.

The decomposition given above can be interpreted as a negative probability mixture of three local operations with probabilities of $p(L_1) = p(L_2) = 1$ and $p(\bar{L}_3) = -1$ that reproduces the non-local unitary operation of the quantum controlled-NOT gate. It is therefore possible to obtain the correct output statistics of the quantum gate by adding the output probabilities of the local operations L_1 and L_2 and subtracting the output probabilities of the local operation \bar{L}_3 . The operation of a non-local quantum gate can then be simulated by performing only local operations and classical communication between the qubits.

3. Probabilities for sequences of gate operations

To decompose an arbitrarily complex quantum circuit, all we need to do is to evaluate the total probability of a sequence of N gate operations. Since the gate operations are linear, and since the output density matrix can be written as a linear combination of the outputs from the three local operations, it is possible to apply the conventional rules of Bayesian statistics. The statistical weight of a sequence i of the local operations L_1 , L_2 and \bar{L}_3 is therefore equal to the product of the statistical weights of each operation. Since the statistical weights of L_1 , L_2 and \bar{L}_3 are $+1$, $+1$, and -1 , the probability $p(i)$

of a particular sequence i of local operations is given by

$$p(i) = \begin{cases} +1 & \text{for even numbers of } \bar{L}_3 \\ -1 & \text{for odd numbers of } \bar{L}_3 \end{cases} \quad (7)$$

In total, there are 3^N possible sequences i . Specifically, there are $(3^N - 1)/2$ negative probability sequences with an odd number of \bar{L}_3 operations, and $(3^N + 1)/2$ positive probability sequences with an even number of \bar{L}_3 operations, for a total probability of one.

In a classical simulation, both positive and negative sequences must be performed with equal (naturally positive) frequency. The probabilities of the quantum process $p_{\text{quant.}}$ are therefore related to the classical simulation probabilities $p_{\text{pos.}}$ and $p_{\text{neg.}}$ of the positive and negative sequences by

$$p_{\text{quant.}} = 3^N (p_{\text{pos.}} - p_{\text{neg.}}). \quad (8)$$

Here, the amplification factor of 3^N expresses the different normalizations of the classical probabilities and the quantum probabilities. Specifically, the classical simulation necessarily replaces the negative frequencies $f_{\text{quant.}} = kp_i$ associated with negative probabilities with positive frequencies $f_{\text{neg.}} = k|p_i|$. As a result, the ratio of the total number of trials needed for the classical simulation to the k trials used in the quantum process becomes

$$\frac{\sum f_{\text{pos.}} + \sum f_{\text{neg.}}}{\sum f_{\text{quant.}}} = \frac{\sum_i |p(i)|}{\sum_i p(i)} = 3^N. \quad (9)$$

The possibility of achieving an exponential speed-up by quantum computation is therefore directly observable as an amplification factor of 3^N that relates the probability differences in the classical simulation to the probability differences observed in the actual quantum operation. It may be worth noting that this result is closely related to the exponential decay of the signal predicted by classical models of NMR quantum computations, as reported in [9]. In fact, (8) and (9) can be interpreted as representations of the minimal signal decrease caused by the classical simulation of the entangling gates, providing a quantitative expression for the conjecture at the end of [9] that “an ultimate signal decrease is the consequence of any attempt to describe entangling unitaries classically”.

The correct output of the quantum circuit can be written as a statistical mixture of the outputs of the 3^N local operations, with the appropriate statistical weights of $p(i) = \pm 1$. The probability $p(m)$ of obtaining a specific measurement result m in the output can thus be written according to standard Bayesian probability theory as

$$p(m) = \sum_i p(m|i)p(i), \quad (10)$$

where $p(m|i)$ is the conditional output probability of sequence i determined from the mixture of local output states obtained by applying sequence i . (10) represents the quantum analog of classical causality, showing that the introduction of negative probabilities permits a detailed analysis of quantum operations in terms of well

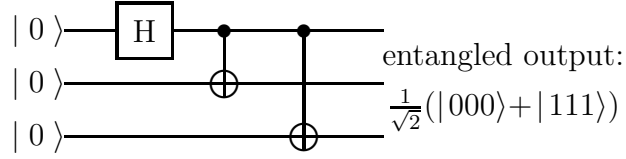


Figure 1. Quantum logic circuit generating a maximally entangled three qubit GHZ state.

separated, non-interfering classical sequences of events. Since the introduction of negative probabilities $p(i)$ is the minimal negative probability necessary to obtain a local description of the entangling gates, this should be the closest possible analogy between quantum and classical processes that works for any combination of local gates and quantum controlled-NOT operations.

4. Simulation of an entanglement paradox

One of the main merits of the negative probability decomposition is the representation of entanglement effects in terms of negative probability mixtures of local alternatives. To see how this decomposition “resolves” the paradoxical aspects of entanglement, it may be instructive to take a closer look at the example of a specific quantum circuit generating a maximally entangled state.

One of the most simple cases is the circuit shown in figure 1, which generates the three qubit Greenberger-Horne-Zeilinger (GHZ) state $(|000\rangle + |111\rangle)/\sqrt{2}$ from a non-entangled product of $|0\rangle$ states by a sequence of one Hadamard gate on qubit one and two quantum controlled-NOT gates that change the states of qubit 2 and qubit 3 according to the state of the control qubit 1. The three qubit GHZ state has the paradoxical property that the product of its X values is always $+1$, but the product of any one X value and the two remaining Y values are always -1 . Since only three of these four properties can be true for any simultaneous assignments of X and Y values to the three qubits, the four probabilities of 1 observed in the GHZ state output are a striking proof of the impossibility of local hidden variable models [18, 19, 20]. It should therefore be interesting to see how the gate operations generate the four correlations.

We can find this out by decomposing the two gate operations into nine sequences of local operations, identifying the conditional probabilities $p(XXX = +1|i)$, $p(XYY = -1|i)$, $p(YXY = -1|i)$, and $p(YYX = -1|i)$. The results are shown in table 1. Specifically, each correlation can be traced to a different sequence of local operations, with $L_2 - L_2$ generating $XXX = +1$ and $L_3 - L_3$ generating $XYY = -1$, while the negative probability operations $L_2 - \bar{L}_3$ and $\bar{L}_3 - L_2$ generate $YXY = +1$ and $YYX = +1$, reducing the total probabilities of these outputs to zero and leaving a probability of 1 for the opposite results of $YXY = -1$ and $YYX = -1$. In all four cases, the remaining eight sequences of local operations result in probabilities of $1/2$.

Table 1. Contributions of the nine sequences of local operations of the circuit in figure 1 to the output probabilities of the four correlations of the GHZ paradox.

Sequence		$p(m i)$ for m given by			
i	$p(i)$	XXX $= +1$	XYX $= -1$	YXY $= -1$	YYX $= -1$
$L_1 - L_1$	1	1/2	1/2	1/2	1/2
$L_1 - L_2$	1	1/2	1/2	1/2	1/2
$L_1 - \bar{L}_3$	-1	1/2	1/2	1/2	1/2
$L_2 - L_1$	1	1/2	1/2	1/2	1/2
$L_2 - L_2$	1	1	1/2	1/2	1/2
$L_2 - \bar{L}_3$	-1	1/2	1/2	0	1/2
$\bar{L}_3 - L_1$	-1	1/2	1/2	1/2	1/2
$\bar{L}_3 - L_2$	-1	1/2	1/2	1/2	0
$\bar{L}_3 - \bar{L}_3$	1	1/2	1	1/2	1/2

Thus the GHZ paradox is “resolved” by separating the sequences that generate the four correlations. This is possible because the negative probabilities in (10) allow conditional probabilities of $p(m|i) \neq 1$ even when the total probability is $p(m) = 1$.

5. Quantum parallelism and uncertainty

The example in the previous section illustrates how negative probabilities can restore locality to the description of quantum processes. Without changing the mathematical structure of the formalism, it is thus possible to represent the non-local coherences of the Hilbert space formalism as non-interfering negative probability mixtures of local alternatives. The advantage of this approach is that it establishes a very close analogy between classical probabilistic computation and the use of entanglement in quantum computation. This may be especially useful for the interaction between experiment and theory, since the experimental verification of quantum processes is usually based on local measurement statistics. Hence the effects of entanglement are obtained by combining the correlations observed in separate measurements, based on the notion that the outcomes observed separately on identically prepared systems all represent equally valid features of the actual quantum process occurring in parallel. The simulation of quantum processes by negative probabilities corresponds to this empirical notion of quantum parallelism, providing a description of quantum processes that is closer to the experimentally accessible evidence than the Hilbert space formalism [12, 13].

Since it is obvious that actual measurement outcomes can never have negative probabilities, it may be appropriate to reflect a bit on the justifications for the use of negative probabilities in quantum mechanics. In the example of the three qubit GHZ paradox, experiments are limited to measuring either X or Y . As a result of this uncertainty limit on local quantum measurements, it is not possible to construct an actual experiment where the negative probabilities of table 1 would result in

an impossible prediction. Thus the uncertainty principle “covers up” the negative probabilities and the assignment of negative values to joint probabilities of X and Y can be consistent with the experimental evidence. One of the consequences of this possibility is that it invalidates the claim of Einstein, Podolsky, and Rosen [21] that an element of reality must be attributed to measurement outcomes that can be predicted with 100% certainty. Instead, probabilities of 100 % can still be conditional, since they may arise from a cancellation of negative and positive joint probabilities for alternative results. It is therefore possible to resolve entanglement paradoxes if one is willing to give up the notion of a non-empirical reality beyond the uncertainty limit.

In the case of the GHZ state generation, it is clear that the output measurements cannot distinguish between the nine sequences of operations given in table 1, making the details of the quantum process experimentally inaccessible. The assignment of negative probabilities $p(i)$ is then consistent with all possible measurement results. In the classical simulation, the output probabilities are determined by separating positive and negative sequences and assigning attenuated positive probabilities of $p_{\text{pos.}}(i) = p_{\text{neg.}}(i) = 1/9$. It is then possible to trace the probability of $p_{\text{quant.}}(XXX = +1) = 1$ to the difference between $p_{\text{pos.}}(XXX = +1) = 3/9$ and $p_{\text{neg.}}(XXX = +1) = 2/9$, amplified by a factor of 9 according to (8). Thus, the classical simulation makes the details of the process accessible at a cost of reduced probabilities and hence reduced certainty about the results. Effectively, there appears to be a fundamental trade-off between the uncertainty limited access to details of the quantum process and the enhanced precision of the observable outcomes. This trade-off can be expressed in the “currency” of potentially negative probabilities. In the context of the present work, this indicates that uncertainty about the actual sequence of logical operations is the price to be paid for the possibility of an exponential speed-up in quantum computation.

6. On the universality of negative probability simulations

The essential feature of the simulation presented in this paper is that it can be applied to arbitrary networks of controlled-NOT gates and local unitaries. Since this is a universal set of gates, any arbitrary quantum process can be simulated in this manner. It is certainly possible to find more efficient simulations for specific processes and algorithms, but such simulations would depend on specific features of the processes (e.g. a restriction of gate operations such as the one considered in the Gottesmann-Knill theorem [11]). However, no conceivable quantum process can exceed the speed-up given by the probability amplification of 3^N , since there always exists a corresponding classical process that reproduces $p_{\text{quant.}}$ in terms of $p_{\text{pos.}}$ and $p_{\text{neg.}}$ according to (8). Thus the probability amplification of 3^N provides an upper limit for the possible computational speed-up of universal quantum computers.

In addition to this quantitative limit, the universal correspondence between classical probabilistic computation and quantum computation established by the use of negative probabilities may also provide a key to the microscopic analysis of quantum effects

beyond the uncertainty limit. In particular, the negative probability analysis describes conditional probabilities that could be tested experimentally, either by interrupting a statistical sample of the computations by projective measurements [22], or by using weak measurements with negligible back-action [23, 24, 25]. In the case of weak measurements, the correspondence of the non-classical features to negative probabilities is already well established (see e. g. [5, 8]), and the possible implications for quantum computation have recently been discussed in [6]. Moreover, it has been shown both theoretically and experimentally that weak measurements can be performed using a quantum controlled-NOT gate to implement the measurement interaction [26, 27]. It is therefore possible to describe the weak measurement as a part of the quantum circuit, providing a “resolution” of the paradox of post-selected weak values outside the range of possible eigenvalues in terms of the quantum parallelism of the two qubit gate.

Finally, it may be worth considering the possible extensions of the present work to other entangling interactions. In principle, the present approach is not limited to the quantum controlled-NOT gate, and its extension to other universal gates such as the recently realized quantum Toffoli gate [28] may provide further insights into the general relation between entanglement capability and computational speed-up. On a more fundamental level, it may also be interesting to consider a direct simulation of quantum interactions using a negative probability decomposition of the interaction mediated by a Hamiltonian into conditional local operations [29]. This approach might establish a general connection between computational speed-up and the interaction dynamics of quantum systems.

7. Conclusions

It has been shown that a universal quantum computer can be simulated by a closely related classical probabilistic computation, where the effects of entanglement are simulated by assigning negative statistical weights to a well defined part of the outcomes. Since each two qubit gate is simulated by a selection of one of three local operations, the exponential speed-up of a quantum computation involving N two qubit gates can be described by the factor of 3^N , representing the number of possible sequences of local operations needed to simulate a single quantum operation of the circuit. This statistical expression of exponential speed-up represents an upper limit for any speed-up achieved in quantum computation.

In addition to providing a fairly simple and compact recipe for a classical simulation of any arbitrary quantum process, the negative probability decomposition described in this paper can also be used to analyze general non-classical features of quantum processes. As illustrated by the example given above, it is then possible to explain not only the possibility of computational speed-up, but also the paradoxical aspects of entanglement and weak measurement in a single unifying framework. The simulation of quantum computation by negative probabilities may therefore be the key to a more intuitive and consistent understanding of quantum systems in general.

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